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(54) Abstract Title
A combined spatial equalization and adaptation technique for a radio communications receiver with an adaptive antenna system

(57) An adaptive antenna system (8) has a plurality of antennas (10, 12, 14) arranged to detect radio signals, a spatial filter (16) coupled to the antennas operates to combine the signals and scale them with antenna weight coefficients. Signals combine coherently when they arrive at the antenna system from within an angle subtending from the antenna system, the subtending angle being steered by the spatial filter (16). The receiver has a receiver controller (44) coupled to the antenna system which operates to adapt the antenna coefficients consequent upon an error signal determined from the radio signal. The adaptive antenna system further comprises a dither insertion means (50, 52) coupled between the antennas and the spatial filter, arranged to introduce a plurality of dithering signals which cause the receiver controller (44) to adapt antenna coefficients to steer a beam from the antenna in a direction corresponding to the direction of arrival of the radio signal.

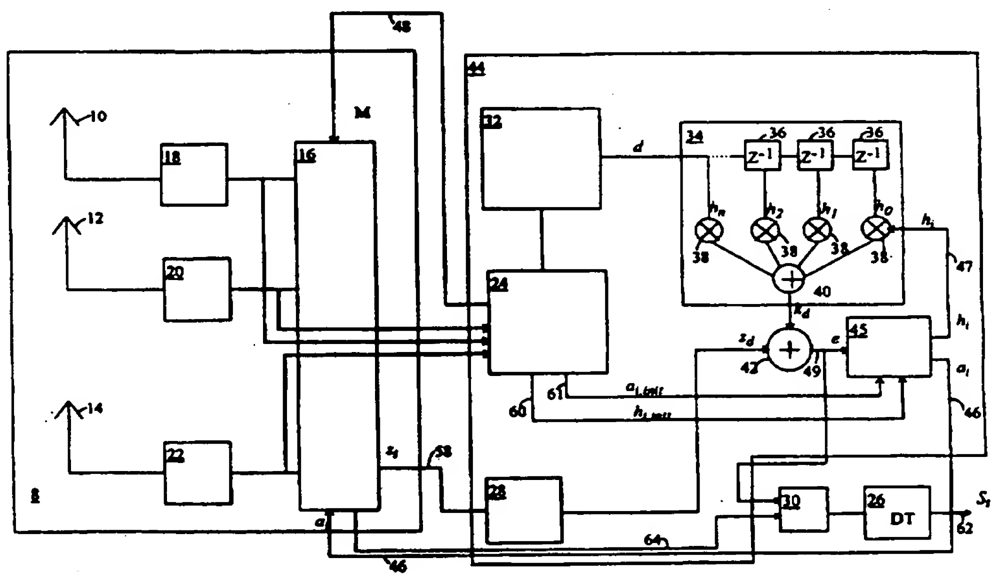

Fig. 3

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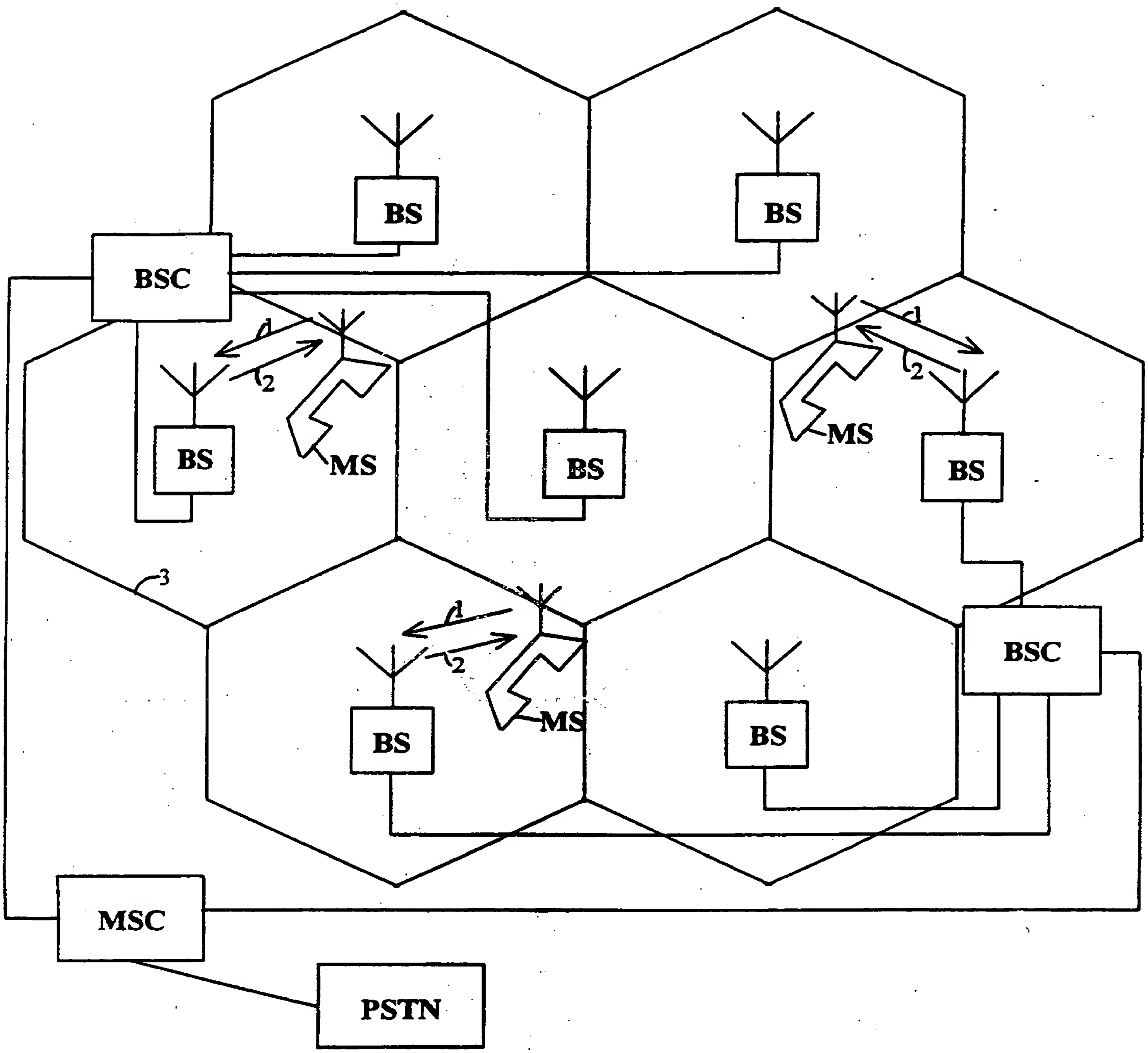

Fig. 1

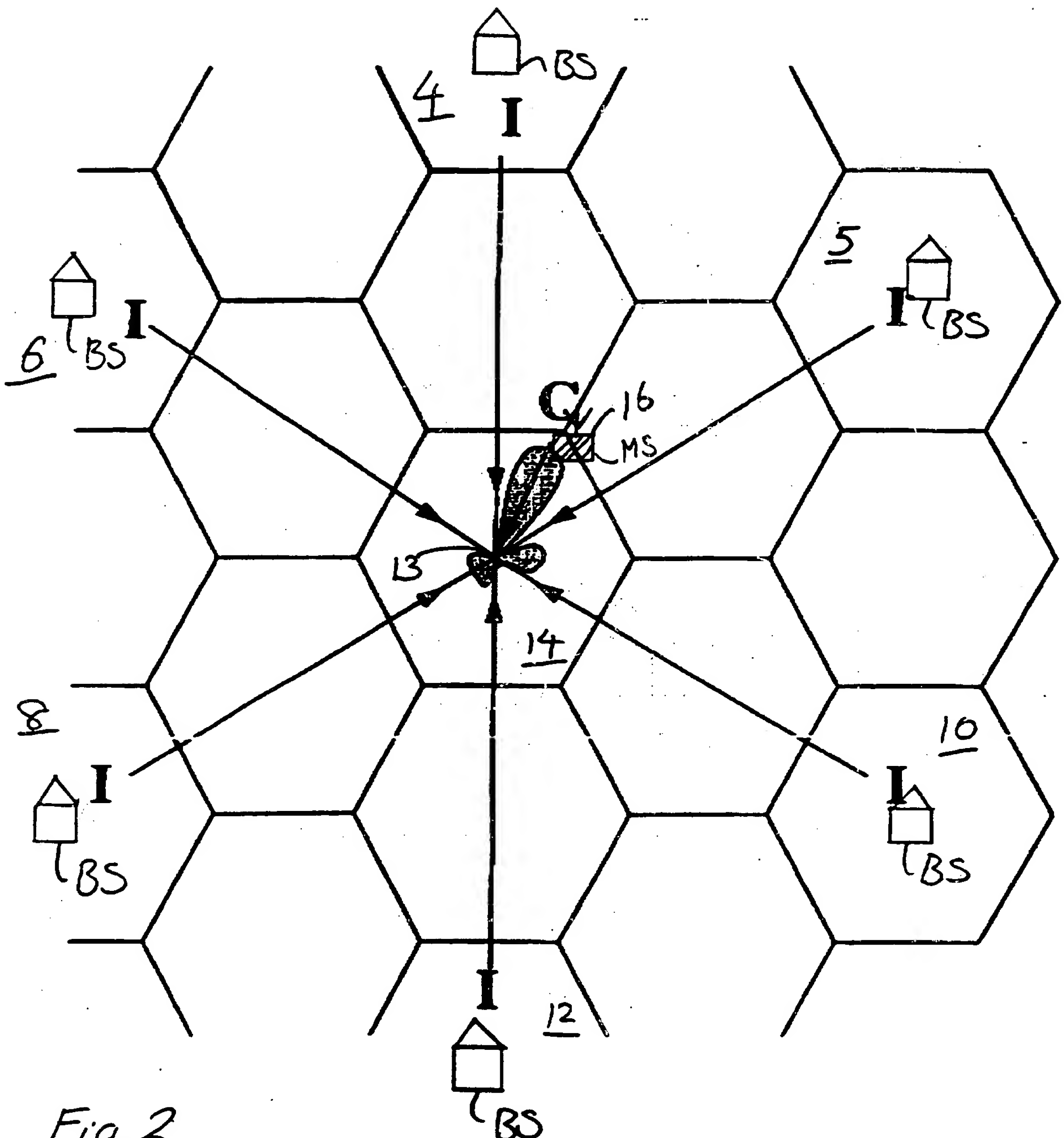

Fig. 2

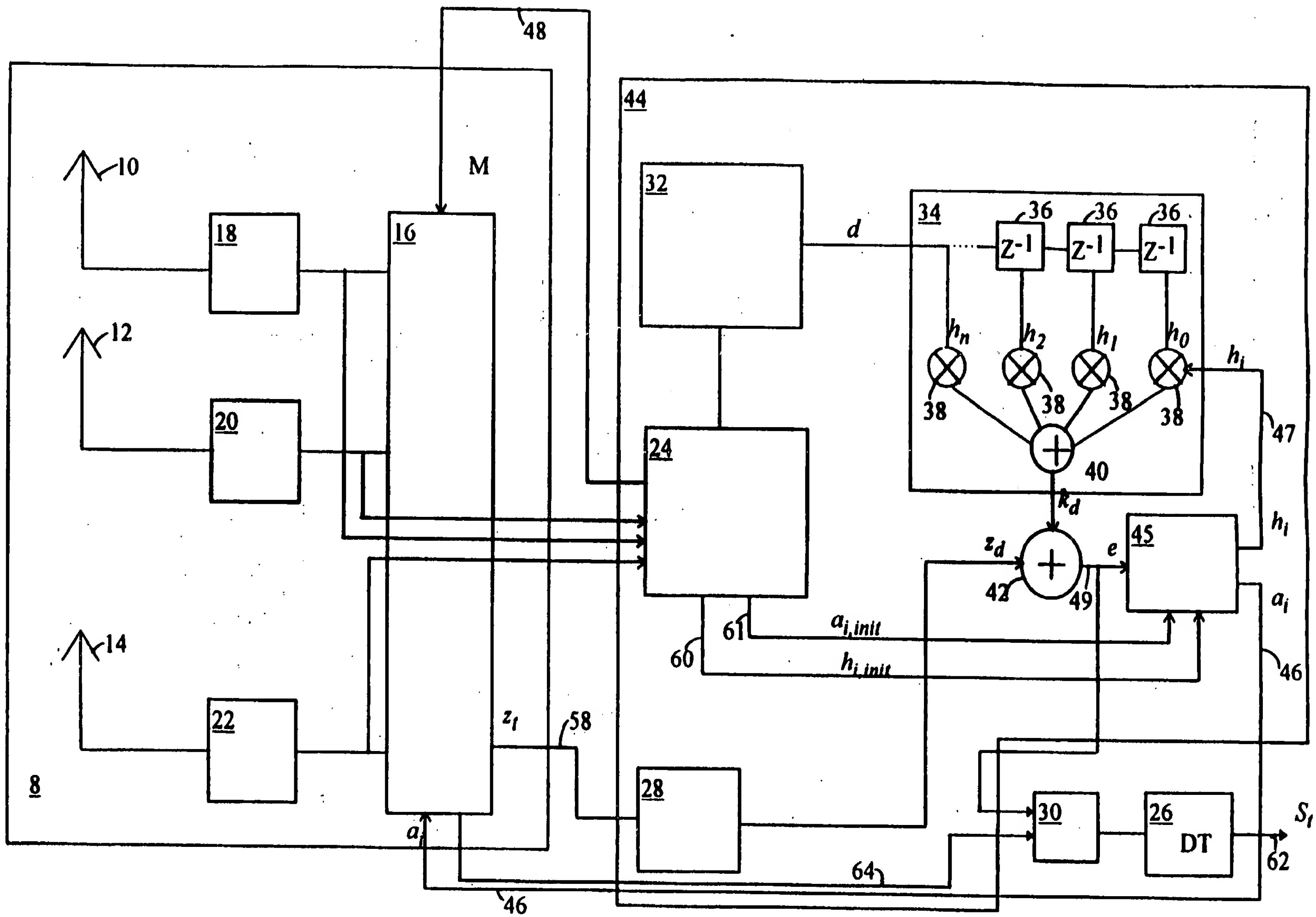
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Fig. 3

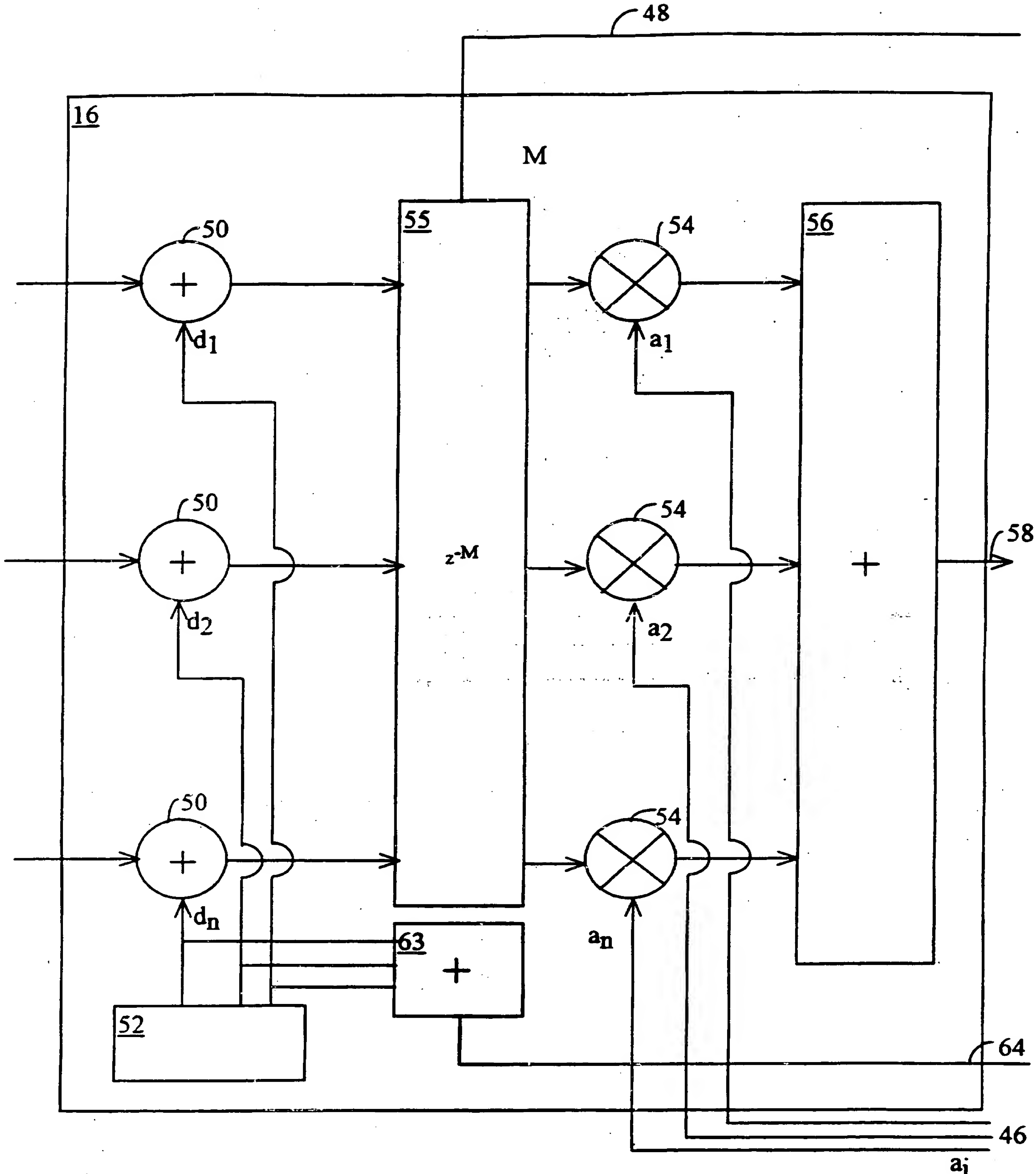

Fig.4

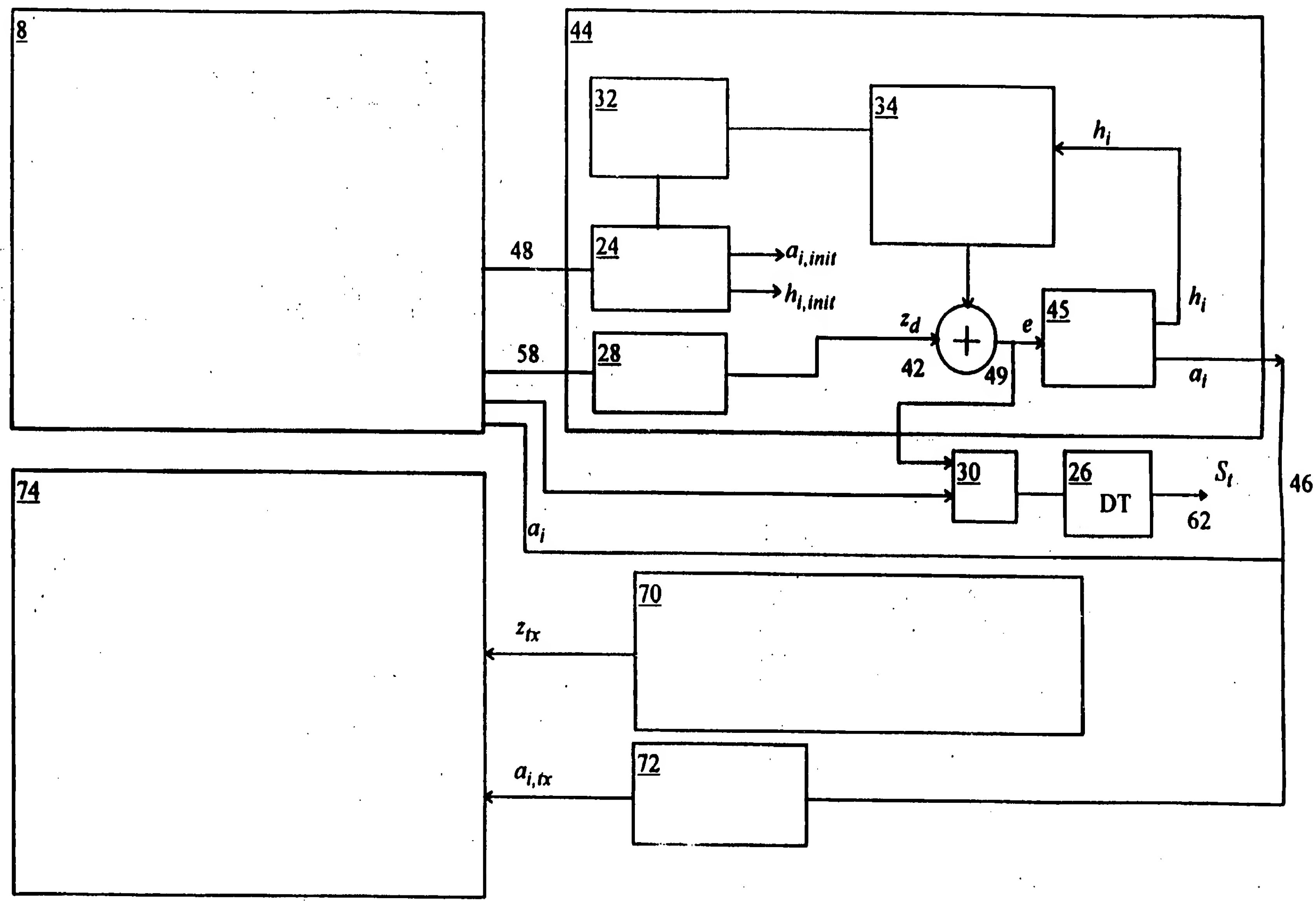
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Fig. 5

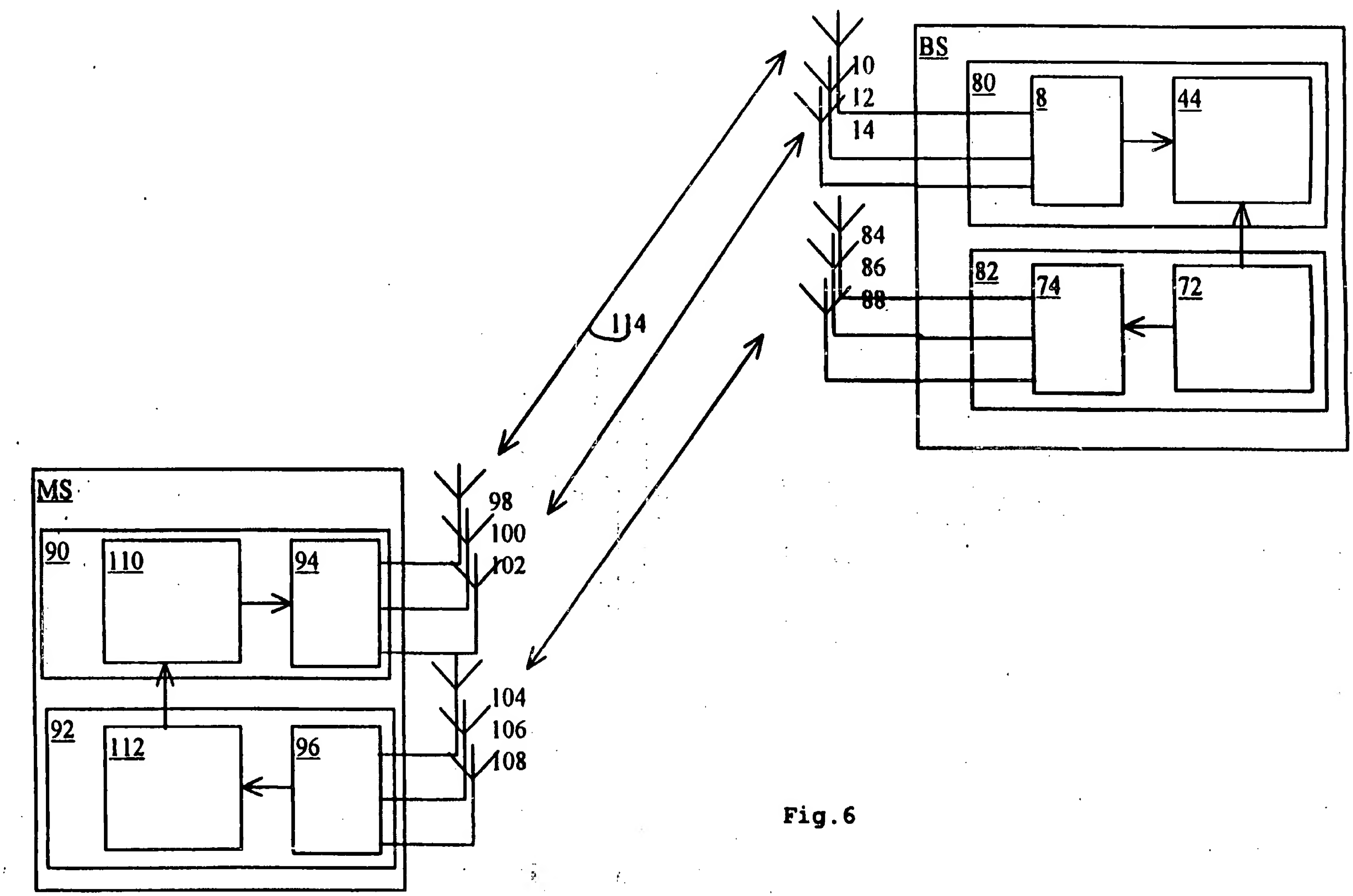
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Fig.6

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Description of invention

Radio Communications Receiver and Method of Receiving Radio Signals

The present invention relates to radio communications receivers which operate to detect radio signals and to generate data communicated by the radio signals. More particularly, the present invention relates to radio communications receivers which include antenna systems arranged to facilitate detection of the radio signals, thereby effecting improved communication of the data which the radio signals represent. Furthermore the present invention relates to methods of receiving radio signals.

Data is communicated using radio signals by modulating the radio signals with the data in some way, and transmitting the radio signals via the ether to a receiver. The radio signals are detected by the receiver, which re-generates the data represented by the radio signals. In order to transmit the radio signals and to facilitate reception of the radio signals, radio communications apparatuses are known to be provided with antenna systems which operate to radiate the radio signals in the case of a transmitter and to detect the radio signals in the case of the receiver.

Radio communications are often degraded and sometimes even prevented by unwanted interfering radio signals which are detected by the antenna system of the receiver and which corrupt a wanted radio signal. The corruption has a detrimental effect on the detection of data communicated by the wanted radio signal with a result that at least some of the data may be erroneous. The interfering signal may, for example, be produced by a third party wishing to disrupt radio communications effected by the wanted signal.

In cellular mobile radio communications systems, interfering signals are an inherent characteristic of the system. Cellular mobile radio systems operate to provide mobile radio telephone communications to a plurality of users of the system contemporaneously within an allocated portion of radio frequency spectrum. This is effected, *inter alia*, by allocating communications channels supported on radio frequency carrier signals between the mobile users of the system. Furthermore, to provide an efficient use of the allocated radio frequency spectrum, some users are allocated communication channels using the same carrier frequencies in accordance with a frequency re-use arrangement. The frequency re-use arrangement, has an effect of re-allocating radio frequency bandwidth to different mobile users for use in communicating radio signals contemporaneously. As far as possible, mobile users are separated in distance, so that the effects of the resulting interference are minimised. The re-allocation of carrier frequencies facilitates an improvement in the number of telephone conversations which can be contemporaneously supported by the mobile radio system, using the allocated portion of radio frequency spectrum. However an inherent characteristic of such a frequency re-use arrangement, is that receivers of the radio signals must be arranged to accommodate interfering signals transmitted from commonly allocated carrier frequencies.

Adaptive antennas are antenna systems which operate to provide optimum gain to a wanted signal arriving from a certain direction. Correspondingly such antenna systems operate to suppress interfering signals which are spatially displaced from the wanted signal and therefore have a different direction of arrival at the antenna system. Adaptive antenna systems are characterised by a plurality of antennas which are spatially displaced and arranged to be coupled via multiplicative tap weights to a combiner. Effectively, the spatial displacement of the antennas in combination with the tap weights provides a spatial filter.

By arranging for the tap weights to alter the amplitude and phase of the radio signal received from the antenna with which it is associated, a wanted signal arriving from a particular direction will be combined at the combiner to the antennas and consequent upon the value of the tap weights, the signals from each of the plurality of antennas will be coherently combined so as to provide maximum gain for signals arriving from or radiated from within a certain volume subtended from the antenna. This volume is known as a beam, and the process of forming the radio signals into a beam or forming a coherent detection beam for received signals is known as beam forming.

In general, energy from other sources will arrive at a combiner of the antenna system via variable paths and, as a result of the choice of tap weights, add incoherently. Thus a polar plot of a beam pattern of such an antenna system (power gain against azimuth angle) will point in the direction of the angle of arrival of the wanted signal. The technique of beam forming and others in the adaptive antennas art are described in a publication entitled 'Beam Forming: A Versatile Approach to Spatial Filtering' by Barry de van Veen and Kevin M B Buckley published in the I.E.E.E A.S.P. magazine April 1988.

In order to make maximum use of the energy of a transmitted signal, and thereby substantially optimise a power of the received wanted signal as compared to the power of the interfering signals (maximise carrier to interference ratio), a radio system which is arranged to operate with an adaptive antenna system should arrange for a beam pattern of the transmitter and beam pattern of the receiver to point in a direction of the wanted signal. To this end, known antenna systems are provided with direction of arrival systems which operate to determine a direction of arrival of the wanted signal at the receiver. An example of a direction of arrival process is known as ESPRIT which is disclosed in an article

entitled 'ESPRIT - Estimation of Signal Parameters Via Rotational Invariance Techniques' by Richard Roy and Thomas Kailath published in the I.E.E.E Transactions on Acoustics, Speech and Signal Processing Volume 37, No. 7 July 1989. However, such direction of arrival estimation algorithms are complex and require that a receiver of the radio system is provided with a substantially high performance data processor in order to determine the direction of arrival in real time. It will be appreciated from the above discussions that a technical problem exists in providing a radio communications receiver with an antenna system which maximises gain to a wanted signal, which does not require a processor to determine a direction of arrival of the wanted signal. The technical problem is addressed by a radio communications receiver according to the present invention.

According to the present invention there is provided a radio communications receiver comprising an adaptive antenna system having a plurality of antennas arranged to detect a plurality of at least partially de-correlated versions of a radio signal, and a spatial filter coupled to said plurality of antennas, which operates to scale said plurality of versions of said radio signal with a plurality of antenna coefficients, and to combine said scaled plurality of radio signal versions, said receiver further comprising a receiver controller coupled to said antenna system which operates to adapt said antenna coefficients, said radio signal versions combining coherently when said radio signal arrives at said antenna system from within a beam steered by said spatial filter in dependence upon said antenna coefficients, wherein said adaptive antenna system further comprises a dither insertion means coupled to said plurality of antennas and arranged to introduce a plurality of dithering signals, which cause said receiver controller to adapt said antenna coefficients so that the beam of said antenna system is steered in a direction corresponding to a direction of arrival of said radio signal.

The Applicant has discovered that by arranging for dithering signals to be introduced into the versions of the received radio signal, a receiver adapted and arranged to adjust the antenna coefficients of a spatial filter in dependence upon the received combined radio signal, will cause the coherent beam of the antenna system to point in a direction in which the radio signal arrives at the antenna system.

The receiver controller may adapt the antenna coefficients consequent upon an error signal determined from said radio signal. The error signal may be formed by the receiver controller by comparing the radio signal with local reference signals combined with an estimate of the channel impulse response. The radio signal may include known predefined signals generated from a reference data sequence and the receiver controller may further include an initialisor coupled to the spatial filter of the antenna system which operates to determine the estimate of the channel impulse response. The initialisor may further operate to determine initial antenna weight coefficients.

The receiver controller may further include a data processor which operates to adapt the antenna weight coefficients so that the error signal is minimised. The data processor may further operate to adapt the channel impulse response estimate so that the error signal is minimised.

Advantageously the antenna system may include N antenna elements and the dithering signals may be N dithering signals. Such signals may be un-correlated in beam/pattern space and may therefore be un-correlated in coefficient space.

The dithering signals are arranged to represent additional interferes coming from a plurality of directions wherein each of said dithering signals is arranged to be generated in

accordance with a pre-determined direction, the addition of dithering signals being formed in a beam/pattern space.

Advantageously the dithering signals may be removed from said combined radio signal by a dither removal means which operates to subtract said combined dither signal from said error signal. The dither removal means may be a low pass filter, in a case of a high frequency dither signal.

According to an aspect of the present invention there is provided a method of receiving radio signals, said method comprising the steps of;
- receiving a plurality of versions of said radio signal;
- weighting respectively each of said plurality of versions of said radio signal with one of a corresponding plurality of antenna weight coefficients;
- combining said weighted versions of said radio signal;
- adapting said antenna coefficients in accordance with said combined weighted radio signal; and
- adding a plurality of dithering signals to said plurality of versions of said radio signals, which dithering signals have an effect of facilitating adaptation of said antenna coefficients so that a coherent beam formed by the antenna system points substantially in a direction at which said radio signals arrive at said antenna system, thereby substantially increasing gain of said wanted signal.

Advantageously the radio signals may include known predefined signals generated from a reference data sequence, and the method may further comprise the steps of;
- generating a channel impulse response from said known predefined signals;
- generating an error signal from a comparison of said known predefined radio signals with local reference data sequences combined with said channel impulse response estimate; and
- adapting said antenna coefficients so that said error signal is substantially minimised.

One embodiment of the present invention will now be described, by way of example, only with reference to the accompanying drawings, wherein;

FIGURE 1 is a conceptual block diagram of a known mobile radio system;

FIGURE 2 is a conceptual schematic diagram representing a layout of cells forming part of a mobile radio system;

FIGURE 3 is a schematic block diagram of a receiver including an adaptive antenna system;

FIGURE 4 is a schematic block diagram of the adaptive antenna system shown in Figure 3;

FIGURE 5 is a schematic block diagram of a communicator which includes the receiver illustrated in Figure 3;

FIGURE 6 is a schematic block diagram of parts of a mobile telephone system embodying the example communicator shown in Figure 5.

An illustrative embodiment of the present invention will be described with reference to a mobile radio communication system, an example of which is shown in Figure 1. Mobile radio communications systems such as the Global System for Mobiles (GSM) operate to provide mobile communications between mobile telephones and base stations of a mobile radio network. In Figure 1, mobile stations MS, which operate within the mobile radio system are provided with a means for both transmitting and receiving radio signals 1, 2, to and from a base station BS with which the mobile stations MS are affiliated. The mobile radio network comprises a plurality of base stations BS which are inter-connected via a base station controller BSC which is further connected to a mobile switching centre MSC. The mobile switching centre is thereafter connected to a public switch telephone network PSTN. By arranging for data representative of voice signals

to be communicated between the mobile stations and the base stations, the mobile radio network operates to effect a mobile telephone system such that, for example, communication between a mobile station and a telephone connected to the public switch telephone network is effected via the base stations, base station controller and the mobile switching centre.

With a mobile radio communication system such as the GSM system, each base station has a pre-determined set of communication frequencies with which the mobile stations may communicate with the base station. Associated with each base station is a cell which is defined as an area in which radio communications may be effected with the base station. This is illustrated in Figure 1, by the boundary line 3, surrounding each cell. It is a feature of such mobile radio systems that in order to provide optimum use of an allocated band width of radio frequency spectrum, base stations are allocated a set of radio frequency carrier signals, in accordance with a frequency re-use pattern associated with each cell served by one of the base stations. An effect of the frequency re-use pattern is that at least some of the base stations are allocated the same set of carrier frequencies, albeit with an arrangement such that those base stations are physically separated by as great a distance as possible. Separating the base stations by as great a distance as possible facilitates a reduction in power of unwanted signals transmitted between these base stations and mobile stations on the same frequency as that of a wanted signal. Frequency re-use provides a means for optimising the capacity of a mobile radio system in terms of a number of communications channels which can be contemporaneously supported within a radio coverage area and radio frequency spectrum allocated to the mobile radio system.

As a result of the aforementioned frequency re-use, a base station BS transmitting a wanted signal to a mobile station

MS, will experience interference from unwanted signals transmitted between mobile stations and base stations in other cells on the same frequencies as those used in the cell with which the mobile station is associated. Therefore, although frequency re-use provides a means for increasing the capacity of the mobile radio network, the interfering signals generated from cells using common frequencies, will reduce the integrity of the data communicated by the wanted radio signal. Mobile stations are therefore arranged to operate in accordance with a pre-determined carrier (power of the wanted signal) to interference (power of a total of the interfering signals) ratio. This is illustrated in Figure 2, where base stations BS are shown to be disposed in cells 4, 5, 6, 8, 10, 12, which are using common frequencies to that used by a mobile station MS communicating a wanted signal with a base station 13 in a cell 14, with which it is associated. Interfering signals I may be seen in Figure 2 where the base station 13 associated with cell 14 is communicating with a mobile station 16. A characteristic technical problem of mobile radio networks is therefore to provide receivers of the radio signals with a means for suppressing the un-wanted interfering signals I, so that a distance between base stations may be reduced, thereby increasing the capacity of the mobile radio network, or correspondingly improving the integrity of data communicated thereby.

To address this characteristic problem, the Applicant has developed a combined spatial equalisation and adaptation technique for an adaptive antenna system, which has an effect of suppressing interfering signals I arriving at angles spatially displaced from an angle of arrival of a wanted signal C, and providing increased gain to this wanted signal, in the presence of multi-path propagation effects. This is achieved by adapting antenna coefficients of the adaptive antenna system in accordance with an error signal generated from a comparison of the received radio signals with locally generated reference signals produced by convolving pre-

determined data sequences with a channel impulse response estimate. The channel impulse response estimate is representative of the effects of propagation on the radio signals between the transmitter and the receiver. This process and apparatus is described in our co-pending patent application filed at the German Patent Office, Filing No. 19639414.7. This disclosure provides an arrangement for spatial equalisation by adaptive antennas for time varying signals. A further disclosure provided in a further co-pending patent application filed at the German Patent Office, Filing No. 19604772.2 provides a spatial equalisation and adaptive antenna process and apparatus for time invariant signals. Reference to the above co-pending German Patent Applications provides an illustration or an embodiment of an arrangement wherein the antenna coefficients of an antenna system are adapted in accordance with the reference signals received with the radio signals. In order to provide an illustration of the embodiment of the present invention which will shortly be described, one technique for effecting spatial equalisation by an adaptive antenna system will be briefly described.

In the above mentioned German Patent Applications, a receiver is disclosed which has an adaptive antenna system arranged to provide spatial equalisation to signals for a time division multiplexed mobile radio communications system which may be, for example, the GSM system. As is well known to those familiar with the GSM system, information representative of a portion (20 milliseconds) of captured voice signals is converted into digital data and transmitted along with a training sequence in one of a number of pre-determined time slots on a carrier frequency. As such, at pre-determined points in time, the transmitted radio signal includes a section of predefined radio signals generated in accordance with a sequence of digital data which is known to the receiving radio station. This sequence of digital data is known as a training sequence. The training sequence is used

to provide a means from which the receiving station may estimate a model of the impulse response of the communications channel experienced by the radio signals, and to synchronise the receiver to the radio signals received within the time slot.

In order to suppress interfering signals at a receiver in the mobile radio system and to maximise antenna gain to a wanted radio signal, a receiver according to the invention disclosed in German Patent Application No. 19639414.7 is arranged to include elements as shown in Figure 3. In Figure 3 a plurality of antennas 10, 12, 14, are arranged to detect radio signals transmitted by a wanted signal source. However unwanted interfering radio signals are also detected. The antennas 10, 12, 14, form part of an adaptive antenna system 8, which further includes a spatial filter and combiner element 16, which provides for signals detected by each of the antennas to be combined into a composite signal. The adaptive antenna system 8, further includes a down converter and base band processor 18, 20, 22 for each of the antennas in the receiver. Each of the down converter and base band processors 18, 20, 22, operates to down convert the received radio signals detected by the antennas from a carrier frequency to a base band frequency corresponding to information modulated onto the carrier frequency. Furthermore the base band processors 18, 20, 22, operate to generate digital samples corresponding to the analogue base band signals down converted from the received versions of the radio signals. Each of the base band digital representations of the received signals detected respectively by each of the antennas 10, 12, 14 are fed to an initialisor 24, and to the spatial filter and combiner element 16.

Spatial filter and combiner element 16 serves to generate a combined base band signal representative of the received radio signals. The initialisor 24, provides an initial set of antenna weight coefficients and an initial channel

estimate, (based on the known training sequence). The combined base band signal is fed from the spatial filter and combiner element 16, via a signals separator 28, to an adder 42, which forms an error signal as described below. The signals separator 28, separates the signal parts to the effect that signals resulting from the known mid-amble training sequence are removed from the signals generated from the unknown data which are fed to the adder 42. The error signals generated by the adder 42, are fed to a detector 26 via a dither signal remover 30, which may be for example a filter, in which case the provision of the combined dither signals by conductor 64 is not required. Also shown in Figure 3 is a data store 32, coupled to the initialisor 24, and to a reference signal generator 34. The detector 26, performs a maximum likelihood sequence estimation (MLSE) based on an error signal e, which is generated at the output of an adder 42, via the conductor 49. The generation of the error signal e will be described shortly. The reference signal generator 34, comprises a finite impulse response filter which has a shift register comprising delay elements 36, and coefficient multipliers 38, each output of which is coupled to a combiner 40. The output of the combiner 40 is fed to a first input of the adder 42. The output from the signal separator 28 feeds a second input of the adder 42. The output of the adder 42, which delivers the error signal, feeds a time-variant estimator 45, which operates to estimate the antenna coefficients a_i and to determine the channel model impulse response coefficients h_i. The antenna coefficients a_i are fed from an output of the time-variant estimator 45, via a conductor 46 to a first input of the spatial filter and combiner element 16. A further input to a spatial filter and combiner 16 is fed from an output of the initialisor 24. The channel model impulse response coefficients determined by the time-variant estimator 45, are fed to the reference signal generator 34 via a conductor 47. The time-variant estimator 45, is initialized with the coefficients $a_{i,init}$ and $h_{i,init}$ determined from the training

sequence of the received radio signal by the initialisor 24. The initial channel estimate, and initial antenna coefficients are fed to the time-variant processor 45 provided via the conductors 60, 61.

The data store 32, initialisor 24 reference signal generator 34, adder 42, signal separator 28 and time-variant estimator processor 45, together form the receiver controller 44, which operates to optimise a carrier to interference ratio of received radio signals, by controlling the adaptive antenna system 8, to optimise gain to a wanted signal arriving at the antenna system from a defined direction.

The spatial filter and combiner element 16 is shown in more detail in Figure 4 where parts also appearing in Figure 3 bear identical numerical designations. Base band signals from each of the base band processors 18, 20, 22, are fed to inputs respective of adders 50, which serve to add to the base band signals a number of dithering signals fed on a second input thereto from a dithering signal generator 52. The sum of the base band signals and the dithering signals d_i are thereafter fed to a first input of antenna coefficient scalers 54, via a delay block 55. The delay block 55, introduces a delay to the effect of synchronising the receiver to the received radio signals as will be explained shortly. The antenna coefficient scalers 54, serve to scale each of the respective base band signal samples with one of a plurality of coefficients a_i. The antenna coefficients are fed on a second input to the scalers 54 via conductor 46. Each of the weighted base band signals is thereafter combined by a combiner 56 and fed via a conductor 58 to the inputs of the elements 24, 28 of the receiver controller 44 as hereinbefore described.

As will be appreciated by those skilled in the art, although the illustrative embodiment of the present invention has been described with reference to a time division multiple access

system, with a joint optimisation of the antenna and channel model coefficients, the present invention also finds application with other forms of multiplexing, such as code division multiple access, and in other forms of detection and optimisation of coefficients. Furthermore, as will be appreciated, conversion of radio signals to base band form may be effected at different points in a receiver processing chain. Therefore, although the base band processors 18, 20, 22 have been shown coupled to each of the respective antennas 10, 12, 14, the base band processors could have been connected to an output of the spatial equaliser combiner 16. However, as will be appreciated, this would require summation and multiplication of signals as effected by the spatial equaliser and combiner element 16 at a radio frequency. Therefore the embodiment shown in Figure 3 is preferred.

The base band processors 18, 20, 22, as herein before described, serve to down convert and analogue to digital convert the received signals which are thereafter fed to the spatial equaliser and combiner element 16. The spatial equaliser is formed by the combiner 56, and the antenna coefficient scalers 54, which are arranged to weight each of the received signals by an antenna coefficient a_i , where $i \in \{1....N\}$ and N is the number of antennas. The antenna coefficients a_i are fed to the scalers 54 via a conductor 46. The antenna weight coefficients a_i are representative of a spatial channel estimate and serve to form the antenna pattern into a beam such that signals arriving from a given direction within a volume determined by the beam pattern are combined coherently when combined by the combiner 56. Combined signals are thereafter output on conductor 58. Other elements in the adaptive antenna 8, are the delay means 55 which serves to delay the receive signal in accordance with a synchronisation estimate corresponding to a delay or time shift experienced by the received signals in transmission. This delay is represented by a number of samples M which is fed to the delay means 55 by a conductor

48 as shown. In another embodiment of the present invention the delay could also be placed after the combiner, in which case the adaptive antenna itself would not contain the delay means.

A dithering signal d_i, generated by the dithering signal generator, is added to each of the base band signals. Operation of the dithering signal generator will be described shortly. Referring back to Figure 3, the combined signal z_t is fed to the initialisor 24, and to the signals separator 28. As already mentioned the initialisor 24, operates to generate an initial estimate of the antenna weight coefficients $a_{i,init}$ and an initial estimate of the channel model impulse response coefficients $h_{i,init}$. This is effected, for example by the technique disclosed in the German patent application 19604772.2. The initialisor 24, performs a further operation which is to compare the local reference data sequence with a determined temporal position of the training sequence in the received signal for a number of locations. A least squared error between the local reference data and that of the temporal position of the training sequence in the received data serves to provide an indication of the delay M, experienced in the transmission of the radio signals. It is this delay M which is fed to the spatial equaliser and combiner block 16 on conductor 48.

As herein before explained, the initialisor 24, provides the initial estimates of the antenna weight coefficients and channel model impulse response coefficients on conductors 60, 61, to the time-variant estimator 45. The time-variant estimator thereafter adapts the antenna coefficients and channel model impulse response and feeds these to the spatial equaliser and combiner 16, and to the reference signal generator 34, via conductors 46, 47. These estimates are updated from these initial values, by the time-variant estimator 45, in accordance with a time variation produced *inter alia* by Doppler frequency shift on the received radio

signal. The detector 26 forms a maximum likelihood sequence estimator (MLSE) or a near maximum likelihood sequence estimator which operates to compensate for the effects of inter-symbol interference and fading experienced by the received radio signals and generate signals representative of the data conveyed by the radio signals. This is conveyed on conductor 62 and is shown as the symbols S_t.

As already explained, the signals extractor 28, operates to extract from the received signals that part not corresponding to the unknown data communicated by the radio signals, either side of the known training sequence data. Each symbol of unknown data is fed to the first input of the adder 42. A second input to the adder 42, is fed with a reference signal generated by the reference signal generator 34. The data store 32 is coupled to the reference signal generator 34, and operates to feed pre-determined local reference symbols corresponding to each possible symbol which may have modulated the radio signals to the input of the finite impulse response filter. Reference signal generator 34, therefore operates to convolve the local reference data sequence corresponding to the memory of the channel with the channel impulse response estimate. This is combined and fed to the second input of the adder 42. By subtracting the reference signal k_d from the received predefined signals z_d the error signal e, is formed which is fed to the time-variant estimator 45, and to the detector 26. The time-variant estimator 45, determines subsequent estimates of antenna weight coefficients a_i and channel impulse response estimate coefficients h_i from the latest error signal e. The detector 26 adds the squared error signal to a path metric determined for the state of the channel, in accordance with the MLSE algorithm.

The model variable corresponding to the signal formed by the reference signal generator k_d is representative of one possible sequence of data convolved with the channel impulse

response estimate. Thus the multi-path effects caused by the propagation of the radio signals are simulated with successively arriving signal components being superimposed to form a common signal. The time-variant estimator 45, operates to generate the antenna coefficients a_i and the channel model impulse response estimate coefficients h_i in accordance with a least squares error *e* for each possible data sequence of the received data z_d. The time-variant estimator operates to adapt the antenna coefficients a_i such that the least square error *e* is maintained to be a minimum. A further condition for the solution of the square error is that of a constraint in that not all antenna weighting factors a_i and coefficients of the channel impulse response h_i are equal to 0. Therefore, and in order to achieve an unambiguous solution, an additional constraint is introduced; the sum of the squared channel coefficients is forced to 1 by appropriate scaling.

As will be appreciated, instead of a solution to a problem of least square error, other algorithms may be used to the effect of minimising deviation of the signal *e*. Instead of joint optimisation of antenna and channel coefficients, a separate optimisation may be employed and a different normalisation constraint may be selected.

The receiver as hereinbefore described is used to combine the process of adapting the antenna coefficients in accordance with an estimate of the channel impulse response. However, it has been discovered that where there is only a small number of interfering signals, a beam formed by the antenna system by the adaptive antenna weighting coefficients does not point in a direction where the wanted signal is arriving with maximum power especially if the wanted signal and one of the interferers arrive from similar directions. As such, a direction of arrival algorithm such as the ESPRIT algorithm as hereinbefore mentioned would be required in order to determine the direction of arrival of the wanted signal.

However, it has been discovered that by introducing spatial dithering signals into the adaptive antenna system for each of the N antenna elements, a spatial channel estimate is produced which has the effect of forcing the beam into a direction in which the received signals are arriving. This procedure is hereinafter described as spatial dithering.

The dithering signals are arranged to represent additional interferers coming from a plurality of spatially separate and uncorrelated directions. The introduction of the spatial dithering signals is effected in beam/pattern space by generating one interferer per desired direction or in coefficient space in which one interferer signal is generated per antenna element.

In order to avoid a situation where the dithering signals will be effectively introducing more noise into the received radio signals and thereby degrading the performance of the detector 26, it is desirable to introduce a dither signal removal means 30 which serves to extract the dithering signals from the received radio signals fed to the detector 26. For example, the dithering signal extractor may be a low pass filter since a dithering signal may be a comparatively high frequency signal whereas the base band signal may extend from 0Hz to a frequency in the order of 80kHz to 135kHz. Alternatively, and as shown in Figures 3 and 4, the dithering signal combiner 63, is provided within the adaptive antenna system 16, which is coupled to each output of the dithering signal generator 52. The dithering signal combiner 63, generates on the conductor 64 a signal representative of a combined dithering signal which is fed to the dither signal removal means 30, which subtracts the combined dithering signal from the error signals fed to the data detector 26.

The embodiment of the present invention herein before described provides a means for generating a spatial channel impulse response which has an effect that the beam formed by

the antenna system points in a direction of arrival of the received wanted radio signals. This is achieved without a requirement for a computationally complex direction of arrival algorithm. As such, the antenna coefficients may be used for adaptation of an antenna system for a receiver which forms part of a communicator, which is arranged to transmit as well as receive. To this end, an adaptive antenna system may be provided for the transmitter, so as to focus the transmitted signals into a beam pointing in the direction of arrival of the received signals. The transmit antenna coefficients a_{tx}, may be determined from the antenna coefficients a_{rx} determined by the receive antenna system, by appropriately adapting the coefficients a_{rx} to reflect a change from receive to transmit. If the transmit signal is on a different frequency, an appropriate conversion of the antenna coefficients is required in correspondence with the change of frequency. An example of such a communicator is shown in Figure 5, where parts also appearing in Figures 3 and 4 bear identical numerical designations. In Figure 5, the communicator includes parts of the receiver of Figure 3 and a transmitter 70, arranged to feed a base band digital signal, to an adaptive transmit antenna unit 74. Also shown in Figure 5 is a transmit controller 72, which operates to adapt the antenna coefficients a_i received from the time-variant estimator 45 of the receiver controller 44 on conductor 46, to the effect that the transmit antenna system 72, forms the transmitted signals into a beam, which points in the same direction as that determined by the antenna coefficients for the received radio signals. As will be appreciated the base band signals to be transmitted must be digital to analogue converted and arranged to modulate a carrier at a frequency corresponding to the transmit frequency.

The antenna coefficients generated in accordance with the aforementioned embodiment of the present invention may be used to generate a direction of arrival data for use by an

adaptive antenna system in beam steering, in the transmitter of a base station. The base station receiver determines the direction of arrival of the radio signals, as hereinbefore described, which is then used for beam steering in the transmitter of the base station. This principle may be extended to the effect that direction of arrival information determined in the base station may be communicated to mobile stations of the system, which may be provided with means to interpret this information to the effect that antenna beams formed by transmit and receive antennas may be steered in the direction of the base station. This is illustrated in Figure 6, where parts also appearing in Figures 1, 3, 4 and 5 bear identical numerical designations. In Figure 6, part of a mobile radio telephone system is shown, comprising a mobile station MS, and a base station BS, having a first receiver 80, having a receive antenna system 8, with antennas 10, 12, 14, and a receiver controller 44. The base station BS, also includes a first transmitter 82, also with an antenna system 74, coupled to transmit antennas 84, 86, 88, and a transmit controller 72. The mobile station MS, has a second transmitter 90, and a second receiver 92, each having an antenna system 94, 96, having respectively receive and transmit antennas 98, 100, 102, 104, 106, 108. The second transmitter and receiver 90, 92, also include transmit and receiver controllers 110, 112. In operation, the second transmitter 90, of the mobile station MS is arranged to transmit radio signals 114, to the base station BS, in accordance with a communication process determined by the mobile radio system. The receive antenna system 8, and the receiver controller 44, in the first receiver 80, in the base station operate as herein before described to focus a beam formed by the antenna system 8, so as to point in the direction of the mobile station MS, providing gain to the radio signals received from the mobile station MS. The base station then operates to convert the direction of arrival information, determined by the receiver controller 44, as a set of receive antenna coefficients $a_{i,rx}$, so that radio

signals transmitted by the first transmitter on the down-link to the mobile station MS, are focused into a coherent beam which points in the direction of the mobile station. This is effected as herein before described with reference to Figure 5, for the transmit controller 72 and the transmit antenna system 74, by forming the transmit antenna coefficients $a_{i,tx}$ from the receive antennas coefficients $a_{i,rx}$, or correspondingly by interpreting the receive antenna coefficients $a_{i,rx}$ as in an indication of direction. Thereafter the base station BS, operates to convert the direction of arrival information, into a form which when communicated to the mobile station, provides the mobile station MS, with information with which to correspondingly adapt the coefficients of both the transmit and receive antennas so that coherent beams respectively formed thereby, point in the direction of the base station. This may be achieved in several ways. With this example embodiment, the receiver controller 44, which is coupled to the first transmitter 82, is arranged to communicate direction of arrival data representative of the antenna coefficients of the first receiver 80 to the mobile station MS. This is communicated via radio signals from the first transmitter 82 in the base station, to the second receiver 96, in the mobile station MS. The transmit controller 110, which is coupled to the receiver controller 112 is arranged to adapt the transmit antenna coefficients of the mobile station, in accordance with the direction of arrival data, thereby arranging for a beam of transmitted radio signals to point in the direction of the base station (BS).

Although the aforementioned embodiment of the present invention has been described with the adaptive radio receiver disclosed in German Patent Application 1963941.7, the present invention will also find application with the further invention corresponding to German Patent Application 19604772.2 which is used in the former patent application for initialisation. The latter disclosure of a receiver is

arranged to adapt both the channel impulse response coefficients and the spatial channel estimator coefficients in accordance with a minimisation of an error, and is appropriate for time invariant signals, whereas the former is appropriate for time invariant signals as well as time varying signals.

As will be appreciated by those skilled in the art, various modifications may be made to the embodiments of the invention hereinbefore described without departing from the scope of the present invention. The present invention finds application in any receiver having an adaptive antenna system which is arranged to focus an antenna beam in a direction in which error signals, derived from received radio signals, are minimised. The receiver may be used in any form of radio communications system, but finds particular application in mobile radio communications in which co-channel interferes are present.

CLAIMS:

1. A radio communications receiver comprising an adaptive antenna system (8) having a plurality of antennas (10, 12, 14) arranged to detect a plurality of at least partially de-correlated versions of a radio signal, and a spatial filter (16) coupled to said plurality of antennas(10, 12, 14), which operates to scale said plurality of versions of said radio signal with a plurality of antenna coefficients (a_i), and to combine said scaled plurality of radio signal versions, said receiver further comprising a receiver controller (44) coupled to said antenna system (8) which operates to adapt said antenna coefficients (a_i), said radio signal versions combining coherently when said radio signal arrives at said antenna system (8) from within a beam steered by said spatial filter in dependence upon said antenna coefficients (a_i), wherein said adaptive antenna system (8) further comprises a dither insertion means (50, 52) coupled to said plurality of antennas (10, 12, 14) and arranged to introduce a plurality of dithering signals (d_i), which cause said receiver controller (44) to adapt said antenna coefficients (a_i) so that the beam of said antenna system (8) is steered in a direction corresponding to a direction of arrival of said radio signal.

2. A radio communications receiver as claimed in Claim 1, wherein said receiver controller (44) operates to adapt said antenna coefficients (a_i) consequent upon an error signal determined from said radio signal.

3. A radio communications receiver as claimed in any of Claims 1 or 2, wherein each of said dithering signals (d_i) is arranged to be generated in accordance with a pre-determined direction with respect to said antenna system (8), and said addition of said dithering signals is formed in a beam/pattern space.

4. A radio communications receiver as claimed in any of Claims 1, 2 or 3, wherein said antenna system (8) includes N antennas and there are N dithering signals.

5. A radio communications receiver as claimed in any of Claims 2 to 4, wherein said receiver controller (44) has a reference signal generator (34) and an error signal generator (42), said reference signal generator (34) operating to generate reference signals from pre-determined signals combined with an estimate of the channel impulse response, said error signal generator (42) operating to generate said error signal by comparing said combined weighted versions of said radio signal with said reference signals.

6. A radio communications receiver as claimed in any of claims 2 to 5, wherein said receiver controller (44) further comprises a data processor (45) which operates to adapt said antenna weight coefficients so that said error signal is minimised.

7. A radio communications receiver as claimed in Claim 6, wherein the data processor (45) further operates to adapt the channel impulse response estimate so that said error signal is minimised.

8. A radio communications receiver as claimed in Claims 6 or 7, wherein said data processor (45), is a time-variant or time-invariant estimator.

9. A radio communications receiver as claimed in any preceding claim, and further comprising a data detector means (26) coupled to said antenna system (8) which operates to generate data representative of said radio signal, and a dither removal means (30) coupled between said antenna system (8) and said detector means (26), which operates to substantially remove said dithering signals from said radio signal.

10. A radio communications receiver as claimed in Claim 9, wherein said data detector means (26) is coupled to said antenna system (8) via said receiver controller (44), said data detector means (26) being arranged to detect said data consequent upon said error signal (*e*), and said dither removal means (30) is coupled between said receiver controller (44) and said detector means (26), which operates to substantially remove said dithering signals from said error signal.

11. A radio communications receiver as claimed in any of Claim 10, and further comprising a dither combiner means (63) which is coupled to the dithering signal means (52) and serves to combine said dithering signals, wherein said combined dithering signals are fed to said dither removal means (30), which dither removal means (30) operates to substantially subtract said combined dithering signals from error signal.

12. A radio communications receiver as claimed in Claim 10, wherein the dither signal remover (30) is a low pass filter.

13. A radio communications receiver as claimed in any preceding claim, wherein said radio signal is modulated and transmitted in accordance with a time division multiple access communications system, whereby said radio signals are transmitted within a pre-determined temporal window, and known predefined signals are provided within a part of the temporal window, said receiver controller (44) further including an initialisor (24) which is arranged to generate said estimate of the channel impulse response (h_i), said detector means (26) being an equaliser.

14. A radio communications receiver as claimed in any preceding claim, wherein said radio signal is modulated and transmitted in accordance with a code division multiple access communications system, whereby said radio signal is

modulated by a pre-determined spreading code and contemporaneously transmitted, said known reference signals being provided by a pilot signal forming part of the radio signal, a channel estimator (24) being arranged to generate said channel impulse response estimate by despreading said pilot signal with a local reference data sequence, and said detector means (26) being a rake receiver.

15. A radio communications apparatus for communicating data via radio signals, comprising receiver as claimed in any preceding claim, and a transmitter operatively associated with said receiver, wherein a receiver controller (44) of the receiver operates to generate antenna coefficients $a_{i,rx}$ in dependence upon radio signals received thereby, said transmitter comprising a transmit controller (72) and an adaptive antenna system (74), and said transmit controller (72) operates to convert the receiver antenna coefficients $a_{i,rx}$ into transmit antenna coefficients $a_{i,tx}$ for use in the adaptive antenna system (74), whereby radio signals transmitted thereby are formed into a beam which points in a direction relating to a direction of arrival of said received radio signals.

16. A mobile radio telephone having a radio communications apparatus as claimed in Claim 15.

17. A base station forming part of a mobile radio network, having a radio communications apparatus as claimed in Claim 15.

18. A mobile radio communications apparatus, comprising at least one mobile station (MS) and at least one base station (BS), wherein at least one of said base station (BS) and said mobile station (MS) has a receiver as claimed in any of Claims 1 to 14, and the other of said mobile station and said base station has a transmitter comprising an adaptive antenna system which operates to focus signals transmitted thereby

into a beam in dependence upon transmit antenna coefficients $a_{i,tx}$, wherein said receiver (80) and operates to generate direction of arrival data appertaining to receive antenna coefficients $a_{i,rx}$ generated by a receiver controller (44) in dependence upon radio signals received thereby, which direction of arrival data is communicated to said transmitter (90), which transmitter (90) adapts said transmit antenna coefficients $a_{i,tx}$ in accordance with said direction of arrival data, thereby arranging for said beam of transmitted radio signals to point in the direction of the other of said mobile station (MS) and station base station (BS).

19. A method of receiving radio signals, said method comprising the steps of;
- receiving a plurality of versions of said radio signals;
- weighting respectively each of said plurality of versions of said radio signals with one of a corresponding plurality of antenna weight coefficients;
- combining said weighted versions of said radio signals,
- adapting said antenna coefficients in accordance with said combined weighted radio signals; and
- adding a plurality of dithering signals to said plurality of versions of said radio signals, which dithering signals have an effect of facilitating adaptation of said antenna coefficients so that a beam formed by said antenna system within which said plurality of versions of said radio signals combine coherently, points substantially in a direction of arrival of said radio signal, thereby substantially increasing gain to said wanted radio signal.

20. A method of receiving radio signals as claimed in claim 19, further including the steps of,
- removing said dithering signals from said combined weighted radio signals; and
- detecting data communicated by said radio signals.

21. A method of receiving radio signals as claimed in claims 19 or 20, further comprising the steps of;
- generating an estimate of a channel impulse response from said known predefined signals;
- generating an error signal from a comparison of said radio signals with local reference data sequences combined with said channel impulse response estimate; and
- adapting said antenna coefficients so that said error signal is substantially minimised.

22. A method of receiving radio signals as claimed in any of Claim 21, further including the steps of;
- removing said dithering signal from said error signal; and
- detecting data represented by said radio signal in dependence upon said error signal.

23. A method of receiving radio signals as claimed in Claim 22, wherein the step of removing the dithering signals from the error signals comprises the steps of;
- combining said dithering signals to form a combined dithering signal; and
- subtracting said combined dithering signal from said error signal.

24. A method of communicating radio signals, comprising the steps of;
- generating receive antenna coefficients as claimed in Claim 19 from received radio signals;
- converting said receive antenna coefficients into a transmit antenna coefficients; and
- forming transmit signals into a beam using an adaptive antenna in dependence upon said transmit antenna coefficients, which beam points in a direction of arrival of said received signals.

25. A method of communicating radio signals, comprising the steps of;

- generating receive antenna coefficients from received radio signals in accordance with the method as claimed in Claim 19;
- generating direction of arrival data representative of said receive antenna coefficients;
- communicating said directional of arrival data to a transmitter from which said received radio signals were transmitted;
- generating transmit antenna coefficients in dependence upon said direction of arrival data; and
- forming transmit signals into a beam using an adaptive antenna in dependence upon said transmit antenna coefficients.

26. A radio communications receiver as herein before described with reference to Figures 3 and 4.

27. A radio communications communicator as herein before described with reference to Figure 5 and 6.

The Patent Office

30

Application No:	GB 9804785.5	**Examiner:**	Robert Macdonald
Claims searched:	1-27	**Date of search:**	26 October 1998

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Search Report under Section 17

Databases searched:

UK Patent Office collections, including GB, EP, WO & US patent specifications, in:

UK Cl (Ed.P): H4L(LDSG, LECX)

Int Cl (Ed.6): HO4Q(7/36); G01S(3/16, 3/28, 7/28)

Other: ONLINE: WPI

Documents considered to be relevant:

Category	Identity of document and relevant passage	Relevant to claims
A	US 5369663 (JAMES W. BOND)	
A	US 5299148 (GARDENER et al.)	

X	Document indicating lack of novelty or inventive step	A	Document indicating technological background and/or state of the art.
Y	Document indicating lack of inventive step if combined with one or more other documents of same category.	P	Document published on or after the declared priority date but before the filing date of this invention.
		E	Patent document published on or after, but with priority date earlier than, the filing date of this application.
&	Member of the same patent family		